Dissolved Oxygen and Nitrogen Concentrations in Mactaquac Area Waters, 1968, 1969 and 1972

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ABSTRACT

Penney, G.H. 1987. Dissolved oxygen and nitrogen concentrations in Mactaquac area waters, 1968, 1969 and 1972. Can. MS Rep. Fish. Aquat. Sci. No. 1906. vii + 22 p.

Fish kills in 1968 in the Saint John River below the Mactaquac hydroelectric generating station resulted in the loss of an estimated 200 adult Atlantic salmon (Salmo salar), and the American eel (Anguilla rostrata) was also affected. Symptoms of gas-bubble disease in the dead fish samples indicated this disease was responsible for the mortalities. Potential causes of gas supersaturation in water below Mactaquac were sought. During periods of low generation, water discharged from the turbines contained masses of small bubbles which were rising to the surface of the turbine boils. Quantitative determinations of dissolved nitrogen and oxygen gases in the tailrace waters at various generation levels were conducted in 1968, 1969 and 1972. Results showed that at low generation levels the turbine discharge had become supersaturated with nitrogen gas, which entered the system by way of pressure-venting air valves. Gaseous nitrogen concentrations were as high as 127 percent saturation at the five-megawatt generation level and decreased in general as generation levels increased. Dissolved oxygen concentrations also increased at low generation levels but did not reach supersaturation.

Key words: fish kills, Atlantic salmon, American eel, Mactaquac Dam, hydroelectric generating station, Saint John River, gas-bubble disease, dissolved nitrogen and oxygen, supersaturation, pressure-venting air valves.

RÉSUMÉ

Penney, G.H. 1987. Dissolved oxygen and nitrogen concentrations in Mactaquac area waters, 1968, 1969 and 1972. Can. MS Rep. Fish. Aquat. Sci. No. 1906. vii + 22 p.

Environ 200 saumons atlantiques (Salmo salar) ont été trouvés morts dans la rivière Saint-Jean en aval de la centrale hydro-électrique de Mactaquac en 1968. L'anguille américaine (Anguilla rostrata) a également été affectée. Les symptômes de la maladie de la "bulle d'air" ont été observés dans des échantillons de poissons morts, et cette maladie a été tenu responsable des mortalités. On a recherché les causes possibles de la supersaturation en gaz de l'eau de la rivière en aval de Mactaquac. Durant les périodes de faible production d'électricité, l'eau qui sort des turbines contient des masses de petites bulles qui montent à la surface du remous des turbines. On a effectué en 1968, 1969 et 1972 des déterminations quantitatives de l'azote et de l'oxygène dissous dans l'effluent des turbines à divers niveaux de production. Les résultats démontrent qu'à de bas niveaux de production, l'effluent est supersaturé de gaz d'azote, qui a pénétré dans le système par les soupapes régulatrices de la pression d'air. Les concentrations d'azote gazeux ont atteint 127% de saturation à une niveau de production d'électricité de cinq mégawatts, et elles ont en général diminué à mesure que s'élevait le niveau de production. La quantité d'oxygène dissous a aussi augmenté à de bas niveaux de production, sans toutefois atteindre le point de supersaturation.

INTRODUCTION

Two fish kills occurred in the Saint John River below Mactaquac hydroelectric generating station during the late summer of 1968, resulting in the loss of an estimated 200 adult Atlantic salmon (Salmo salar). The American eel (Anguilla rostrata) also suffered significant mortalities. Symptoms of gas-bubble disease were observed in dead fish collected below Mactaquac.

Gas-bubble disease as the cause of fish mortality has been reported by Marsh and Gorham (1905), by Equsa (1959), and by Bishai (1960), among others. These investigators associated the disease and mortalities with supersaturation of nitrogen gas in water. Marsh and Gorham (1905) found that saturation at the 105 percent level was harmless to fish, but fish were killed at the 127 percent level. Higher saturation levels resulted in shorter exposure times to death. Equsa (1959) suggested that eels and some other species of fish might survive in nitrogen saturation levels up to 115 percent. Harvey and Cooper (1962) found symptoms of gas-bubble disease in sockeye salmon (Oncorhynchus nerka) alevins at gas concentrations as low as 106 percent of air saturation values.

Air supersaturation in water has been observed in both natural and man-made situations. Harvey and Cooper (1962) found that Corbold Creek water became increasingly supersaturated with air when air bubbles were entrained and carried beneath the surface of a deep plunge basin at the foot of a falls. In this case, the increased pressure, where hydrostatic pressure beneath the water surface combined with atmospheric pressure, resulted in additional air being forced into solution. Another natural occurrence of gas supersaturation has been reported by Harvey (1967) from his work at Cultus Lake, where the epilimnion warming rate exceeded the rate of nitrogen loss, resulting in an increased dissolved nitrogen concentration up to 118 percent. Rucker and Tuttle (1948) reported that the well-water supply at Lavenworth Hatchery contained nitrogen at the 144 percent level. Lindroth (1957) described air supersaturation in water which had passed over the spillway at Bergeforsen power station and had been subjected to the combined pressure of one atmosphere plus hydrostatic pressure. Lindroth also stated that no such supersaturation occurred in water passing through the turbine system. Air entering a water-supply pipeline and dissolving under pressure caused gas supersaturation of water at Woods Hole Station (Marsh and Gorham 1905).

Potential supersaturation sources were sought after the fish kills occurred on the Saint John River in 1968. Supersaturation could not have occurred at the Mactaquac spillway because there was no spillage for some months preceeding the fish kills. Indeed, river discharge was at a historical low in 1968, thus restricting power generation to periods of peak electricity demand. During the night hours and over weekend periods, generation was held at minimum levels in order to conserve water.

During low generation periods, it was observed that the water discharged from the turbines to the tailrace contained masses of small bubbles which were rising to the surface of the turbine boils.

Mactaquac generating station operators explained that air automatically enters the turbine system during low generation periods or during a sudden shift in generation load, in order to offset the effects of cavitation. These effects were causing physical damage to turbine blades. Venting the turbine system to allow air to enter releases pressure which builds up under certain operating conditions. The largest quantity of air enters the system at the lowest generation level (5 megawatts or about 1,900 cfs). The air quantity decreases as generation levels increase, up to about 55 megawatts. In 1972, the turbine air-valve system was modified by means of a weighted valve, which prevents any air entry into the turbine system after generation level falls to about 15 megawatts or below.

The fish kills on the Saint John River below Mactaquac in 1968 were attributed to gas-bubble disease resulting from nitrogen supersaturation thought to be occurring when water passed through the turbines at low generation levels. Therefore, quantitative determinations of dissolved nitrogen and oxygen were made at the Mactaquac site in 1968, 1969 and 1972. During this period, tests were conducted to determine if turbine operation did cause supersaturation of water with atmospheric gases, and to gain sufficient understanding of the situation to suggest means for avoiding gas-bubble disease recurrences. The tests were designed to determine differences or changes between dissolved nitrogen and oxygen levels in water from the intake channel - before it entered the turbine system - and from water samples collected from the turbine boils or tailrace at various generation levels. In order to determine how far from the dam supersaturation was carried before equilibrium was reached, samples were collected at various locations extending seven miles downstream. In one sample series, water was collected from various depths in the reservoir above the dam to determine dissolved nitrogen and oxygen concentrations there.

The Mactaquac hydroelectric installation and the approximate water sampling locations are illustrated (Fig. 1). Also, the relationship between the reservoir (headpond), the intake channel and the route of water passage to and through the turbine system to the tailrace are shown (Fig. 2). The proximity of the fish-collection facilities to the expended

water or turbine boil from No. 1 generating unit is illustrated (Fig. 3).

As a standard check against theoretical saturation values for dissolved nitrogen in water, nitrogen levels were measured in distilled water and in Saint John River water that had been aerated at room temperature for up to 48 hours.

This report contains detailed results of tests conducted at Mactaquac in 1968, 1969 and 1972 to determine changes in dissolved nitrogen and oxygen concentrations as a result of turbine operation at various generation levels. It incorporates the data collected in 1968 and 1969 and contained in a report by MacDonald and Hyatt 1969. Most of the literature referred to by them, as well as some of their text, ideas and suggestions, is included. Additional and more recent papers have been listed as references only. This report brings under one cover all the data and information collected to date on gas supersaturation tests at the Mactaquac hydro site.

METHODS

Two series of tests were conducted at Mactaquac in 1968. The first, on November 2, was designed to determine quantitative changes in dissolved nitrogen and oxygen levels between water in the intake channel, before it entered the turbine system, and immediately after it was discharged from the turbine into the tailrace, at generation levels of five and nine megawatts. Water samples were collected with a Kemmerer sampler and transported to the laboratory, where they were analyzed for dissolved nitrogen content by University of Maine consultant chemists, who used a physical stripping process combined with analysis in a gas partitioner (Fisher Model 25V). Duplicate water samples were collected for measurement of dissolved oxygen concentrations by the well-known azide modification of the Winkler method (Standard Methods 1965). These samples were fixed at the time of collection to prevent biological changes and taken to the laboratory for titration.

The second test series, conducted on November 17, 1968, was designed to compare dissolved nitrogen and oxygen levels found in the intake channel with those found in the turbine boil and in tailrace water (0.3 mi below the dam), at generation outputs of 5, 9, 15 and 35 megawatts.

A Kemmerer water sampler was used and samples for dissolved nitrogen determination were taken to the University of New Brunswick, where they were analyzed by a consultant chemist. The dissolved nitrogen analyses were done with a mass spectrometer. Dissolved oxygen concentrations were determined by the Winkler method in the same manner as for the November 2, 1968, test series.

In 1969, several series of tests ere conducted at Mactaquac to determine differences or changes in dissolved nitrogen and oxygen concentrations between intake-channel water, turbine boils at various generation levels, and water at various locations as far as seven miles below the dam. In some test series, dissolved oxygen was the parameter used, and in others both dissolved nitrogen and oxygen were measured. Where dissolved oxygen was the only parameter measured, the Winkler method was used, with the exception of the May 22, 1969, test series when dissolved oxygen was determined with a Hach field kit. In test series where both dissolved nitrogen and oxygen were measured, the Scholander micro-gasometric method was used to measure both dissolved nitrogen and oxygen, and additional dissolved oxygen determinations were made by the Winkler method for comparison purposes. Water samples were again collected with a non-metallic Kemmerer sampler, and for determination of dissolved gas content by the Scholander method, they were transferred to 10-cc glass surgical syringes and taken to the laboratory at the Mactaquac Hatchery. Samples were analyzed as soon as possible after collection to minimize erroneous results due to the tendency of the dissolved gases to reach equilibrium with gases in the surrounding water or the atmosphere.

In 1972, two series of tests were conducted to assess the effects of the turbine air-venting valve system being modified. Water samples were collected from the intake channel and from turbine boil or tailrace water at the 5-, 10-, 15- and 36-megawatt generation levels. Nitrogen and oxygen concentrations were determined by the Scholander method. Additional water samples were collected, and dissolved oxygen determinations were made by the Winkler method as a comparison against the Scholander results. The samples to be analyzed by the Scholander method were transferred to 250-cc bottles with ground-glass stoppers and sealed with parafilm before being taken to the laboratory at Mactaquac hatchery for analyses. This method of transferring water samples to glass-stoppered bottles and sealing them with parafilm was advantageous over the method of transferring them to glass syringes because the glass-stoppered bottles were significantly more water or air tight than the syringes.

To assess the accuracy of the various methods used for determining dissolved nitrogen concentrations, samples of distilled water and one sample of Saint John River water were aerated by bubbling air through them for periods of 24-48 hours. The Scholander and Van Slyke methods for determining dissolved nitrogen levels were compared on distilled water that had been aerated by bubbling air through it at room temperature for 24 hours.

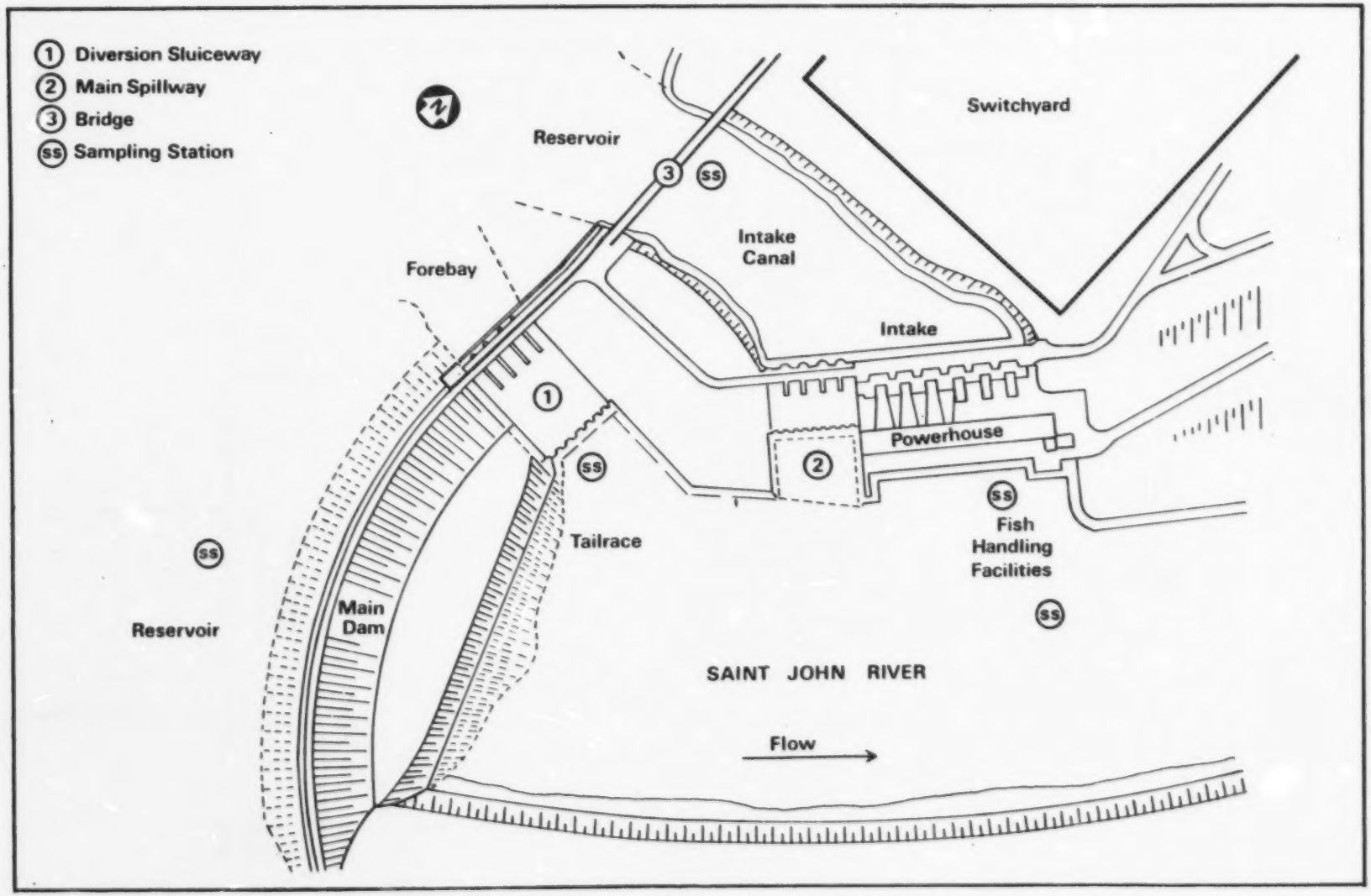

FIG. 1. Approximate water sampling sites, Mactaquac area, Saint John River, New Brunswick.

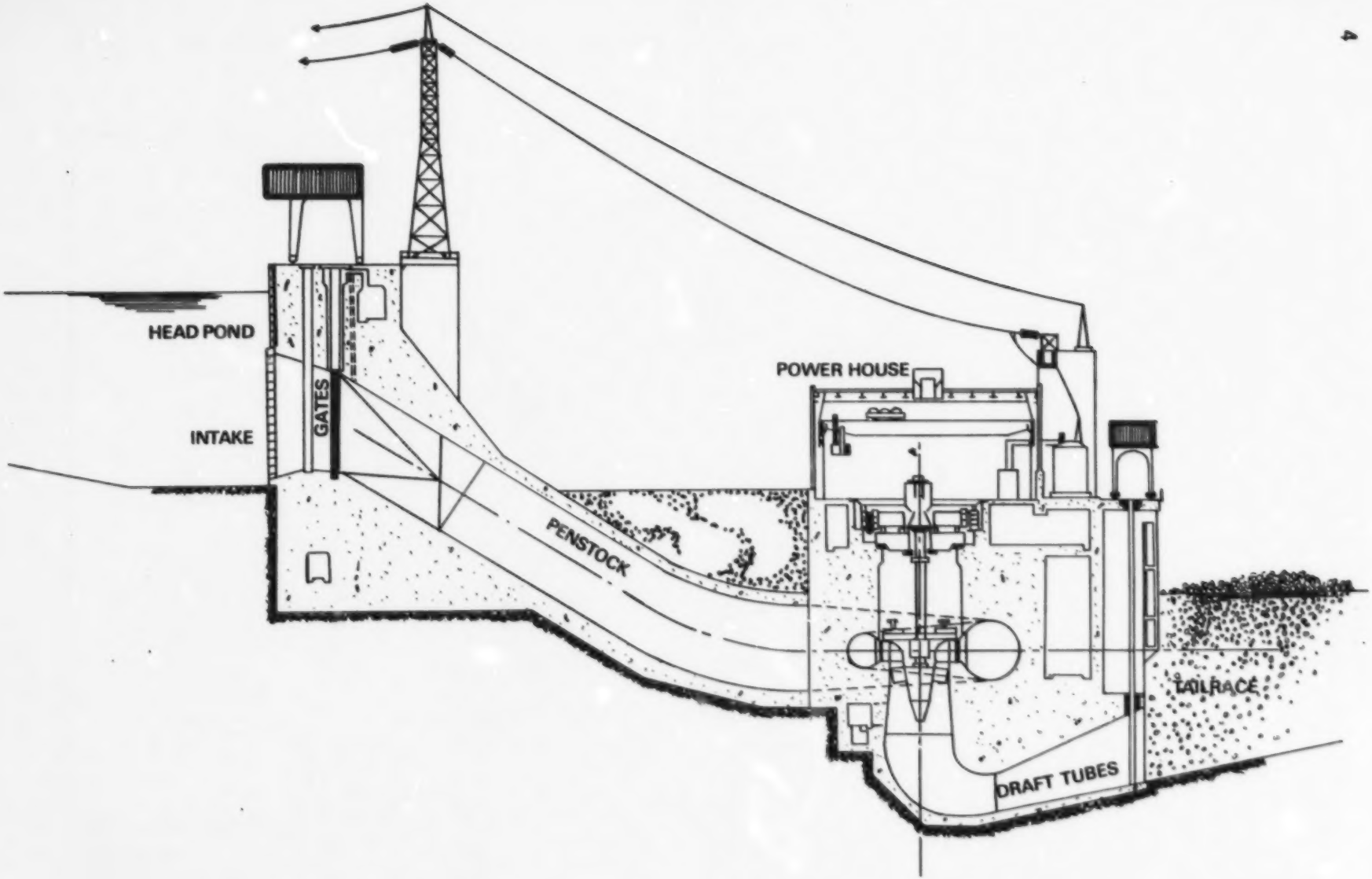

FIG. 2. Sectional view of Mactaquac Dam, showing the route of water passage, from the headpond, through the turbines to the tailrace.

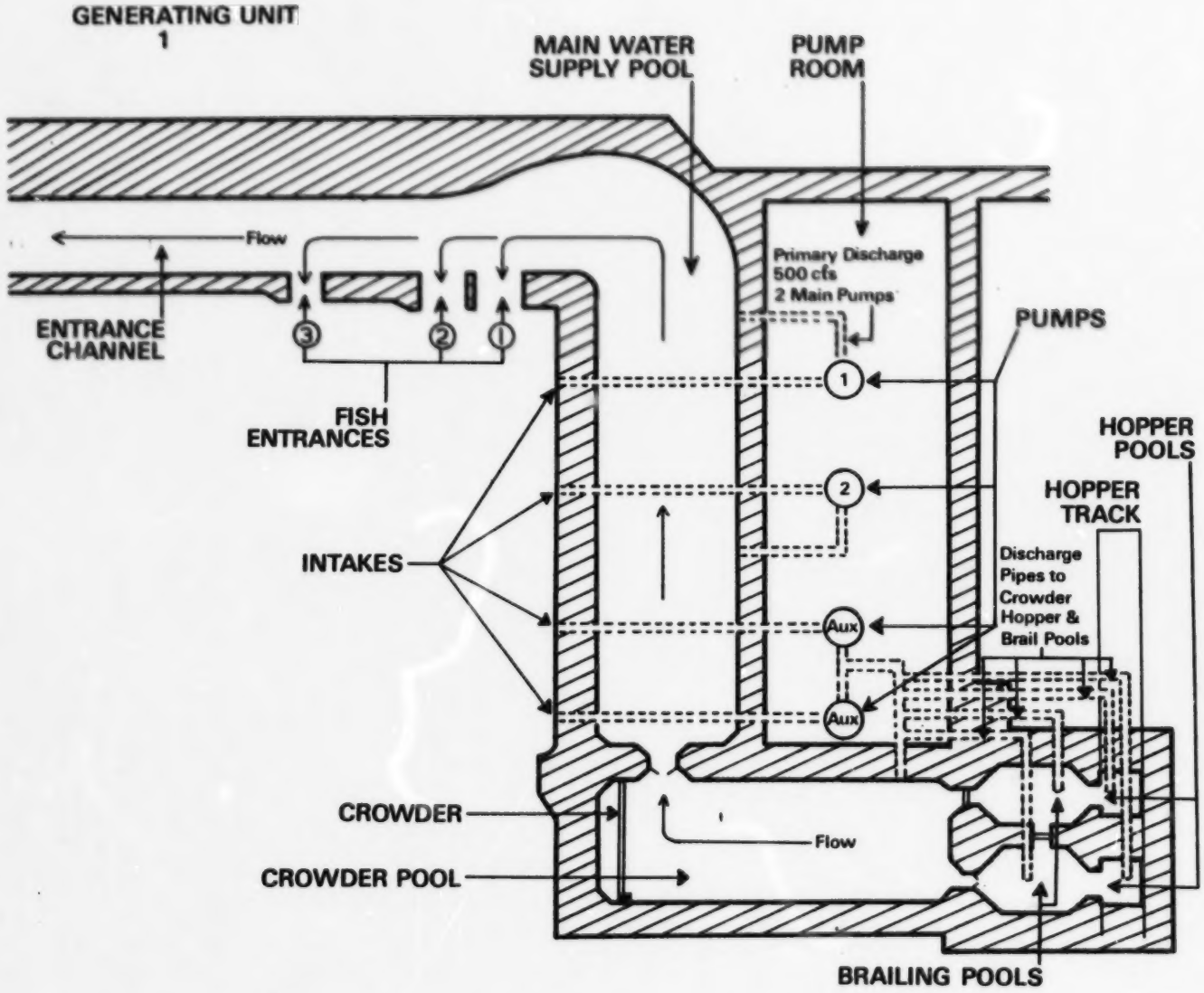

FIG. 3. Mactaquac fish collection facilities, showing the relationship between attraction-water intakes and expended water or turbine boil from Generator No. 1.

RESULTS

Detailed results are tabulated in a series of tables (Appendix). Results of 1968, 1969 and 1972 oxygen and nitrogen analyses (Tables 1 and 2, respectively) are summarized for water samples from the reservoir or intake channel, diversion spillway, turbine boils at various generations levels, and in the tailrace and various other locations below Mactaquac Dam.

In some test series, dissolved oxygen was the only gas measured; and in other test series, both dissolved nitrogen and oxygen were measured. Detailed data (Tables 3-13) from which the summaries were made include: sample location, depth, date, time collected, time processed (when there was a significant delay between collection time and process time for Scholander determinations), ppm and percent saturation of dissolved nitrogen and oxygen, methods used to determine these values, and generation data pertaining to any particular test series. These tables are arranged in order of date of test series, beginning with the first tests in 1968.

DISSOLVED OXYGEN

The values of dissolved oxygen presented in the summary (Table 1) are those determined by the Winkler method, with the exception of the May 22, 1969, results which were determined with a Hach field kit. In this test series, dissolved oxygen levels were actually determined by both the Scholander and Winkler methods, as a check on method accuracy. These two methods gave nearly identical results when samples processed by the Scholander method were completed very soon after collection, with the average of 30 determinations giving 6.7 ppm and 67 percent saturation by the Winkler method, and 6.6 ppm and 66 percent saturation by the Scholander method. The dissolved oxygen results presented in the summary (Table 1) show that tests were conducted over a wide range of generation levels and at a number of locations in the Saint John River below the dam. Only one test was made (May 22, 1969) to determine effects of spilling on change in dissolved oxygen level from that found in the reservoir or intake channel; the test showed that water which passed through the turbulent spill-ways lost some dissolved oxygen on exposure to the atmosphere, while water passing through the turbine system at high generating levels (83 megawatts) remained unchanged. The true dissolved oxygen values here, however, may be different from the observed values because the accuracy of the analytical method used in this test (Hach field kit) is limited.

In the other test series in which dissolved oxygen was determined, 100 percent saturation was not observed. However, the results clearly demonstrate that intake channel water increased its dissolved oxygen content while passing through the turbine system at low generation levels. The greatest increase occurred at the lowest generation levels and became smaller as generation levels increased.

Dissolved oxygen levels found in Saint John River water at various locations below the dam were in general lower than those at their respective generation levels. At a distance of 0.5-1.0 mi. below the dam, they were near to intake channel levels, indicating equilibrium had been reached.

DISSOLVED NITROGEN

Dissolved nitrogen levels (Table 2) were all determined by the Scholander method, except for those of November 2, 1968, which were determined by University of Maine consultant chemists using a gas partitioner (Fisher Model 25V).

The November 2, 1968, results show that water in the intake channel was 85 percent saturated with dissolved nitrogen, and that saturation significantly increased to 125 percent after passing through the turbine system at the 5-megawatt generation level, and to 118 percent at 9 megawatts.

The October 10, 1969, test series was designed to determine changes in dissolved nitrogen concentrations in intake channel water after it had passed through the turbine system at various generation levels. Tests at the 10-megawatt level were carried out when the turbine air-venting system was operating normally, when it was closed, and immediately after it was reopened. Results (Table 9) show that at all generation levels tested the load times were relatively short; therefore, values obtained for dissolved nitrogen may not represent the true values at constant generation loads and related conditions.

The results of the November 4, 1969, tests (Table 10) show that dissolved nitrogen saturation increased by 27 percent at the 7-megawatt level; at 0.5 mi. below the dam, levels were identical to those in the intake channel. The reason for the 7 percent increased saturation at the 105-megawatt generation level is not understood, because at this level atmospheric air is excluded from turbine operation.

The August 20 and September 24, 1972, test series (Tables 11 and 12) show similar results, with the highest increase in percent saturation of intake channel water passing through the turbine system occurring at the lowest generation level (5 megawatts) and decreasing with increasing generation levels. At the 15- and 35-megawatt generation levels, the average values for these dates are almost identical to intake-channel levels. This results from the operation of the modified turbine air-valve venting system, which eliminates entry of atmospheric air to the

turbine at generation levels above 10 megawatts.

In interpreting the 1972 results, it must be noted that the samples collected on August 20 were, due to technical difficulties, only partially analyzed for dissolved nitrogen on that date, and analysis was not completed until August 22 (Table 11). The September 24 samples were, on the other hand, analyzed as soon as possible after collection (Table 12).

SUMMARY

The results of the seven series of tests are summarized as follows:

1. Dissolved oxygen and nitrogen concentrations increased when water passed through Mactaquac turbines at low generating levels.

2. The degree of aeration varied inversely with the generating level in tests up to 35 megawatts.

3. No evidence of aeration was found during generation at the maximum level.

4. Water passing through the spill gates did not gain dissolved oxygen.

5. Equilibrium of dissolved gas content of superaerated water had occurred by the time the water had passed 2½ miles downstream from Mactaquac.

6. It appears that water passing through the turbine system at the 37-megawatt level was not aerated when the vacuum-breaker valves were closed.

7. A water sample from the deeper part of the Mactaquac flowage became supersaturated with nitrogen when raised to the surface. The greatest supersaturation level, however, was not high enough to account for the high levels observed below the hydro-generation station.

8. Nitrogen gas levels in Mactaquac tailrace water during periods of low generation were high enough to cause fish mortalities.

9. The foregoing superaeration data explain the gas-bubble disease fish kills which have been observed below Mactaquac Dam.

RESERVOIR AERATION

Incidental water samples were collected on September 17, 1969, from various depths in the reservoir, in the area of the intake pipes that supply water to Mactaquac Hatchery. These samples were analyzed for dissolved oxygen content by the Winkler method, whereby samples were fixed at the time of collection and titrated at the laboratory. The water samples for dissolved nitrogen determinations were transferred to 10-cc glass surgical syringes, placed in water from the Saint John River at collection time and taken to the laboratory. The syringes, in water, were placed in the refrigerator at 5°C until they could be analyzed, approximately 24 hours later, when both dissolved nitrogen and oxygen contents were determined by the Scholander method. The results (Table 13) serve to illustrate the effects of storage and delayed processing on the dissolved-gas content in water. The mean saturation level of dissolved oxygen found in samples processed on September 17 was 59 percent, and the mean on September 18 was 42 percent. This decrease is probably a result of a combination of biological action and the tendency of dissolved gases to reach equilibrium with those in the surrounding atmosphere or water. The degree of nitrogen equilibrium after the 24-hour storage of water samples is not known. The figures in parentheses represent the saturation levels of dissolved nitrogen and oxygen as calculated at the 5°C temperature to which water samples were exposed for 24 hours before processing, and are somewhat lower than the values calculated at the higher temperatures when the water samples were collected.

ACCURACY CHECK ON METHODS

To obtain an indication of accuracy of the various methods used to measure dissolved nitrogen content in water, experiments were conducted where air was bubbled through samples of distilled water and Saint John River water in an attempt to saturate them with air.

These experiments were as follows:

1. On November 2, 1968, University of Maine consultant chemists bubbled air through distilled water at various controlled temperatures; after 24 hours of aeration, dissolved nitrogen concentrations were determined by a physical gas-stripping process, combined with analysis with a gas partitioner (Fisher Model 25V).

2. On September 25, 1969, a sample of Saint John River water was collected from the Mactaquac reservoir, and aeration of this water was carried out by bubbling air through it at room temperature for up to 48 hours. Identical aeration procedures were carried out at the same time on an equal volume of distilled water. Dissolved nitrogen concentrations were measured by the Scholander method.

3. The final aeration experiment was conducted on September 23, 1972, when distilled water was aerated by bubbling air through it for 24 hours at room temperature. Dissolved nitrogen concentrations in this water were measured by both the Scholander and Van Slyke methods.

The results of aeration experiments give values for dissolved nitrogen in distilled and Saint John River water slightly in excess of theoretical saturation (Tables 14, 15 and 16). The

results determined by the Scholander and Van Slyke methods (Table 16) are almost identical, as are the results obtained by distilled water by the University of Maine on November 2, 1968, and by the Scholander method on September 25, 1969 (Tables 14 and 15, respectively).

The results of aeration experiments do not show the precise accuracy of the various methods used for nitrogen determinations because bubbling of air through water results in an unknown degree of supersaturation and air-equilibrated water should be used (Scholander et al. 1955).

DISCUSSION

Test data indicate that water was aerated during passage through the Mactaquac turbine system at low generation levels. However, they do not indicate the generation range at which aeration ceases to be critical. Closing the vacuum-breaker valves appears to eliminate the aeration hazard, as would be expected, although the data do not consistenly indicate this point. The dissolved nitrogen concentration in the river below the dam reached potentially lethal levels for fish. This supersaturation effect probably caused the 1968 fish kills.

The mechanics of gas solution in the turbine system has not been studied, but a plausible explanation has been derived from information provided by New Brunswick Electric Power Commission personnel. A condition of subatmospheric pressure exists in the turbine system (probably immediately behind the turbine blades), as evidenced by air entrance through the vacuum-breaker venting valves.

As the turbine water leaves the mouth of the draft tube, the depths vary up to 70 feet. At this point, atmospheric pressure plus hydrostatic pressure could result in pressures equivalent to three or four atmospheres. An ambient pressure increase would tend to force air into solution while in the draft tubes at this depth, but the dissolved air concentration might not exceed absolute saturation levels. Upon approaching the surface, tailrace water contained dissolved gas concentrations exceeding theoretical dissolved gas (one atmosphere) saturation levels.

Equilibrium of the dissolved gas tensions apparently does not occur so rapidly. Test data suggest that equilibrium begins as soon as the water reaches the surface of the tailrace, and approaches original gas content level after travelling 2¼ miles downstream. This time interval is estimated to be about one hour. This is approximately of the same order as observed by Harvey and Cooper (1962). They found than the oxygen saturation of Corbold Creek water declined from 110 percent to 105 percent over ¼ mile.

The 1968 fish kills were peculiar because the dead fish were found in the relatively shallow (average 3-5 feet deep) river below the dam but not in the tailrace basin which varies from 20 to 70 feet in depth. It is believed that the function of water depth and consequently of hydrostatic pressure influenced this situation. For example, at a depth of 10 feet, water can normally dissolve about 35 percent more nitrogen than at the surface. A fish at this depth will be unaffected as long as it does not surface quickly. It follows that fish in the depths of the tailrace basin would probably not be affected by the saturation levels of nitrogen that were observed at Mactaquac. However, in the shallower river area at depths of about four feet, where absolute saturation level would be about 114 percent of air, up to 125 percent has been recorded - and it was in this section of the river where fish kills were observed.

The relation between air supersaturation in water and gas-bubble disease of fish is influenced by many factors. The effect of water depth and hydrostatic pressure has been discussed. Susceptibility of fish to gas-bubble disease also varies with species and size of the fish (Marsh and Gorham 1905). At Saint John River, the large salmon and eels appear to have been most affected. No dead juvenile salmon were found. Live salmon parr were observed in the area after the fish kill had occurred.

Another factor which relates supersaturation to fish kill is the length of exposure time. Exposure time to depth was not accurately measured but it was observed that two major fish kills occurred following prolonged periods of sustained minimum generation at Mactaquac. These low-generation periods were 70 and 110 hours, respectively. A minor fish kill occurred in 1969 following 18 hours of minimum generation. In 1968 there were several other long periods of low generation which did not appear to have been followed by fish kills.

The physiology of respiration of fishes involves passage of gaseous nitrogen from solution in the water medium by diffusion, throught the epithelium of the gills and into solution in the plasma of the blood. Osmotic pressure controls the direction and extent of the movement of nitrogen; hence, if concentration of nitrogen in aqueous solution increases, the passage of nitrogen into the blood increases until the gas tension on either side of the gill membrane has equalized. The amount of nitrogen gas that will dissolve in the blood is dependent on the ambient pressure but normally varies from about one to two percent of the blood volume. When the concentration of nitrogen gas in the water exceeds saturation, fish blood becomes similarily supersaturated, with the result that some of the excess nitrogen either coalesces to form bubbles of nitrogen in the blood or is forced out of the blood stream to form bubbles in the body tissues. This latter response

explains the presence of the gas bubbles which appear under the skin of fish or in the organs. The nitrogen that coalesces into bubbles will therefore not be assimilated by the fish; unless the osmotic gradient is reversed, the nitrogen bubbles will eventually reach the heart where a fatal embolism occurs. The fish may live for some period of time following the onset of nitrogen gas precipitation (Marsh and Gorham 1905).

Test results do not provide a simple clearcut solution to the Mactaquac superaeration problem. However, from the information and background obtained, the following suggestions are made (MacDonald and Hyatt 1969).

1. Control generating levels so that 3-hour periods of low generation are alternated with periods of higher generation.

2. Cease turbine operation when generating water is very scarce and must be conserved, and release 2,000 cfs through a spill gate.

3. The New Brunswick Electric Power Commission might continue current efforts to eliminate the need for using the vacuum-breaker system, at least during part of a sustained low-generation period.

4. Inactivate the fish-collection gallery and attraction-water supply during critical periods, so that fish will not be restrained in the relatively shallow water of the collection compartment; or fish should be removed from the collection compartment at intervals not exceeding three hours.

5. Fish showing signs of gas-bubble disease in the collection area should be released to the tailrace, as this is the only deep water where they have a chance to decompress gradually. The attraction water might then be turned off for a few hours to prevent entry of more fish.

6. Request the New Brunswick Electric Power Commission to provide an inspector, who, after being instructed by Department of Fisheries and Oceans personnel, would patrol the river during critical periods and be in constant communication with the power house. When he observes fish in stress, he would inform the plant so that generation could be increased or water could be spilled.

7. A standard requirement should be established, such that in the future no hydroelectric generating station be built that would increase dissolved nitrogen content in water during passage through a turbine system or over a spillway.

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A P P E N D I X

TABLE 1. Summary of dissolved oxygen values for Mactaquac area water samples, 1968, 1969 and 1972.

Sample date	Dissolved oxygen concentrations (% saturation)																			
	Intake channel	Diversion spillway	Turbine boil at various generation levels (MW)											Saint John River at various distances (mi) below dam						
			5	7	9	10	15	33.5	35	60	62	83	100	105	0.3	0.5	1.0	1.5	2.5	6.0	7.0
1968																					
2 Nov	57		85		82										-[1]						
17 Nov	67		93		93		82		72												
1969																					
22 May	103	97										103				105					
7 Jul	73					96										84			73	70	71
28 Jul	74				85											80	63	59		63	62
30 Jul	75										70					72	74	73		79	
10 Oct	66					-[2]		65		73											
4 Nov	69			90										72		70					
1972																					
20 Aug	56		73			63	60		95[3]												
24 Sep	62		82			66	63		65												

1. Additional details on 17 Nov 68 tests and downstream values shown in Table 4.

2. Additional details on 10 Oct 69 tests and DO values at 10-MW load shown in Table 9.

3. This value is questionable; see Table 11.

TABLE 2. Summary of dissolved nitrogen values for Mactaquac area water samples, 1968, 1969 and 1972.

Sample date	Dissolved nitrogen concentrations (% saturation)										
	Intake channel	Turbine boil at various generation levels (MW)									Saint John River 0.5 mi below dam
		5	7	9	10	15	33.5	35	60	100	105	
1968												
2 Nov	85	125		118					115			
1969												
10 Oct	105				-[1]		107					
4 Nov	100		127							107		100
1972												
20 Aug	100	123			106	95		99				
24 Sep	100.5	127			107	103		101				

1. Additional details on 10 Oct 69 tests and dissolved nitrogen values at 10-MW load shown in Table 9.

TABLE 3. Dissolved oxygen and nitrogen values for Mactaquac area water samples, 2 Nov 68.

Sample location	Water Temperature (°C)	O_2 (Winkler)		N_2 (gas partitioner)	
		ppm	% sat.	ppm	% sat.
Intake channel	12.0	6.2	57	15.1	85
Turbine boil					
(5 MW, 2,000 cfs)	12.0	9.2	85	22.1	125
(9 MW, 2,200 cfs)	12.0	8.9	82	20.8	118

TABLE 4. Dissolved oxygen values for Mactaquac area water samples,[1] 17 Nov 68.

Sample location	Water temperature (°C)	O_2 (Winkler)	
		ppm	% sat.
Intake channel			
(16-ft. depth)	7.0	8.0	66
(46-ft. depth)	7.0	8.1	67
Turbine boil			
(5 MW, 1,900 cfs)	8.0	11.2	93
(9 MW, 2,300 cfs)	8.0	11.2	93
(15 MW, 2,800 cfs)	8.0	9.8	82
(35 MW, 4,400 cfs)	8.0	8.5	72
Tailrace, 500 yd. below dam			
(5 MW, 1,900 cfs)	8.0	10.6	88
(9 MW, 2,300 cfs)	8.0	10.5	87
(15 MW, 2,800 cfs)	8.0	10.4	87
(35 MW, 4,400 cfs)	8.0	9.6	80

1. Samples were taken to the University of New Brunswick and refrigerated at approximately 5°C for one week, pending repairs to mass spectrometer.

TABLE 5. Dissolved oxygen values for Mactaquac area water samples, 22 May 69.[1,2,3]

Sample location	Water temperature (°C)	O_2 (Hach kit) ppm	O_2 (Hach kit) % sat.
Intake channel			
(3-ft. depth)	8.3	12	102
(40-ft. depth)	8.6	12	103
Diversion sluiceway	9.7	11	97
Turbine boil			
(#1, 82.8 MW)	9.2	12	103
(#3, 83.6 MW)	9.2	12	103
Saint John River			
(0.5 mi. below dam)	9.4	12	105
(7.0 mi. below dam)	8.3	13	110

1. During the test period, Turbine #2 was also operating at 79.2 MW.
2. Total water discharge of 162,700 cfs was comprised of 56,250 cfs from diversion gates, 69,000 cfs from main gates and 37,450 cfs from the turbines.
3. Headwater elevation of 115.15 ft. and tailwater elevation of 27.40 ft. resulted in an effective head of 87.75 ft.

TABLE 6. Dissolved oxygen values for Mactaquac area water samples, 07 Jul 69.

Sample location	Water temperature (°C)	O_2 (Winkler) ppm	O_2 (Winkler) % sat.
Reservoir			
(3-ft. depth)	18.4	6.8	72
(20-ft. depth)	18.9	6.8	73
(36-ft. depth)	18.4	6.9	73
Turbine boil			
(10 MW, 2,360 cfs)	18.0	9.2	96
Saint John River			
(0.3 mi. below dam)	17.2	8.0	83
(0.5 mi. below dam)	17.8	8.1	84
(2.5 mi. below dam)	17.8	7.0	73
(6.0 mi. below dam)	16.7	6.9	70
(7.0 mi. below dam)	16.7	7.0	71

TABLE 7. Dissolved oxygen values for Mactaquac area water samples, 28 Jul 69.[1]

Sample location	Sample time (hr.)	Water temperature (°C)	O_2 (Hach kit) ppm	O_2 (Hach kit) % sat.	O_2 (Winkler) ppm	O_2 (Winkler) % sat.
Intake channel						
(3-ft. depth)	0800	20.0	8	87	8.6	94
(35-ft. depth)	0800	17.5	6	62	5.2	53
Turbine boil at 9 MW	0540	18.5	7	74	8.1	85
Tailrace						
(500 yd. below dam)	0615	18.5	6	63	7.8	82
Saint John River						
(0.5 mi. below dam)	0630	18.5	7	74	7.5	80
(1.0 mi. below dam)	0645	18.0	6	63	6.1	63
(1.5 mi. below dam)	0655	18.5	6	63	5.6	59
(6.0 mi. below dam)	0710	18.5	6	63	6.0	63
(7.0 mi. below dam)	0730	18.5	6	63	5.8	62

1. During the test period, generation data (Turbine #1) were checked five times (at 0500, 0530, 0600, 0630, and 0700 hours). The following readings remained unchanged throughout:

Generator load - 9 MW
Discharge - 2,300 cfs
Headwater level - 126.7 ft.
Tailwater level - 9.8 ft.
Gate position - 10%
Head cover pressure - 33 psi
Penstock pressure - 14.5 psi
Tailwater visual - Boiling appearance, with small bubbles

TABLE 8. Dissolved oxygen values for Mactaquac area water samples, 30 Jul 69.[1]

Sample location	Sample time (hr.)	Water temperature (°C)	O_2 (Winkler) ppm	O_2 (Winkler) % sat.
Intake channel				
(3-ft. depth)	1430	20.5	7.0	77
(30-ft. depth)	1440	21.5	6.4	72
Turbine boil at 62 MW	1500	19.5	6.5	70
Tailrace				
(500 yd. below dam)	1510	19.5	6.6	71
Saint John River				
(0.5 mi. below dam)	1515	20.0	6.6	72
(1.0 mi. below dam)	1525	20.0	6.8	74
(1.5 mi. below dam)	1535	20.0	6.7	73
(6.0 mi. below dam)	1550	20.0	7.3	79

1. During the test period, generation data (Turbine #2) were checked seven times, as tabulated below:

Time (hr.)	MW	Discharge (cfs)	Headwater level (ft.)	Tailwater level (ft.)	Gate position (%)
1300	72	8,450	126.5	11.9	61
1330	82		126.5	12.0	66
1400	71	8,325	126.5	11.85	61
1430	81		126.5	11.9	65
1500	62	8,650	126.5	11.9	56
1530	68		126.5	11.9	59
1600	62	7,650	126.5	11.9	56
1650	Test finished at 1615 hours, due to required change to operation of Turbine #1.				

2. Also, throughout the test period, vacuum breakers remained closed. Visual appearance of the tailwater was described as - "boiling effect and no small bubbles."

TABLE 9. Dissolved oxygen and nitrogen values for Mactaquac area water samples, 10 Oct 69.[1]

Sample location	Sample time (hr.)	Water temp. (°C)	O_2 (Winkler) ppm	O_2 (Winkler) % sat.	O_2 (Scholander) ppm	O_2 (Scholander) % sat.	N_2 (Scholander) ppm	N_2 (Scholander) % sat.
Intake channel (3-ft. depth)	0720	12.0	7.2	66	7.2	66	18.2	105
Turbine boil (10 MW, 2,350 cfs, 10 min, vacuum breakers open)	0525	11.5	8.3	76	8.5	78	20.6	118
(33.5 MW, 4,200 cfs, 25 min, vacuum breakers open)	0600	11.5	7.2	65	7.8	70	18.6	107
(60 MW, 6,000 cfs, 15 min, vacuum breakers open)	0635	11.5	8.0	73	8.3	76	20.1	115
(10 MW, 2,350 cfs, 10 min, vacuum breakers closed)	0650	11.5	7.8	71	7.95	72	19.95	114
(immediately after vacuum breakers reopened from previous test)	0700	12.0	7.4	68	8.8	80	21.7	125

1. During the test period, additional generation data were recorded as follows:

Time (hr.)	MW	Headwater level (ft.)	Tailwater level (ft.)	Effective head (ft.)
0506	10	128.35	10.3	118.05
0530	10	(Finished first turbine boil test)		
0535	33.5	(Started second turbine boil test)		
0535	33.5	128.35	10.5	117.85
0600	33.5	(Finished second test)		
0619	60	(Started third test)		
0619	60	128.35	10.7	117.65
0638	60	(Finished third test)		
0641	10	(Started fourth test)		
0641	10	128.35	10.3	118.05
0658	(Finished testing - return to normal generating pattern)			

TABLE 10. Dissolved oxygen and nitrogen values for Mactaquac area water samples,[1] 04 Nov 69.

Sample location	Sample time (hr.)	Water temperature (°C)	O_2(Winkler) ppm	O_2(Winkler) % sat.	O_2(Scholander) ppm	O_2(Scholander) % sat.	N_2(Scholander) ppm	N_2(Scholander) % sat.
Reservoir, near hatchery intake pipe								
(3-ft. depth)	0920	9.0	8.2	70	8.8	76	19.2	104
(20-ft. depth)	0930	9.0	8.1	70	8.1	70	19.0	103
(40-ft. depth)	0935	8.5	8.1	69	8.3	71	18.9	99
(60-ft. depth)	0945	8.5	8.1	69	8.4	72	18.1	95
(90-ft. depth)	0950	8.5	8.1	69	8.7	74	19.2	101
Turbine boil								
(7 MW, 2,200 cfs, 1 hr.)	1035	8.5	10.5	90	10.5	90	24.3	127
(105 MW, 12,200 cfs, 1 hr.)	1020	9.0	8.4	72	8.7	75	19.8	107
Saint John River (0.5 mi. below dam)	1105	9.0	8.2	70	8.7	74	19.2	100

1. All samples were processed within 1-5 hours of when collected.

TABLE 11. Dissolved oxygen and nitrogen values for Mactaquac area water samples, 20 Aug 72.[1]

Sample location	Sample time (hr.)	Water temp. (°C)	O_2(Winkler) ppm	O_2(Winkler) % sat.	Processing Date	Processing Time	O_2(Scholander) ppm	O_2(Scholander) % sat.	N_2(Scholander) ppm	N_2(Scholander) % sat.
Intake channel										
(3-ft. depth)	0100	20.0	5.5	60	20 Aug 72	0415	5.0	53	13.8	93
(3-ft. depth)	0100	20.0	---	--	22 Aug 72	1415	5.5	60	14.2	96
(23-ft. depth)	0050	20.0	5.1	55	20 Aug 72	0355	4.7	52	12.1	82
(23-ft. depth)	0050	20.0	---	--	22 Aug 72	1500	5.3	57	15.3	108
(55-ft. depth)	0030	20.5	5.0	54	20 Aug 72	0320	4.4	49	10.5	71
(55-ft. depth)	0030	20.5	---	--	22 Aug 72	1530	5.0	54	14.2	97
Turbine boil										
(5 MW)	0325	19.0	6.9	73	22 Aug 72	1120	6.6	70	18.6	123
(10 MW)	0545	19.0	5.9	63	22 Aug 72	1045	5.8	62	16.0	106
(15 MW)	0845	20.0	5.5	60	22 Aug 72	1315	5.1	55	14.0	95
(35 MW)	1140	21.0	8.6	?	22 Aug 72	1345	5.1	56	14.5	99

1. During the test period, additional generation data were recorded as follows:

Time (hr.)	MW	Discharge (cfs)	Headwater level (ft.)	Tailwater level (ft.)
0001	5	2,110	128.55	12.30
0100	5	2,110	128.60	11.20
0200	5	2,110	128.65	10.70
0300	5	2,110	128.75	10.50
0400	10	2,350	128.80	10.40
0500	10	2,350	128.85	10.40
0600	10	2,350	128.90	10.20
0700	15	2,680	128.95	10.40
0800	15	2,680	128.95	10.40
0900	15	2,680	128.95	10.40
1000	35	4,340	128.95	10.70
1100	35	4,340	128.95	10.75
1200	35	4,340	128.95	10.80

TABLE 12. Dissolved oxygen and nitrogen values for Mactaquac area water samples, 24 Sep 72.[1,2]

Sample location	Sample time (hr.)	Water temp. (°C)	O_2(Winkler) ppm	O_2(Winkler) % sat.	Time processed	O_2(Scholander) ppm	O_2(Scholander) % sat.	N_2(Scholander) ppm	N_2(Scholander) % sat.
Intake channel									
(3-ft. depth)	0600	16.0	5.8	58	0710	6.0	60	15.9	100
(3-ft. depth)	1630	17.0	6.5	67	1800	6.2	63	15.9	102
(26-ft. depth)	0550	16.0	6.3	63	0645	6.1	60	15.8	99
(26-ft. depth)	1625	17.0	6.2	63	1735	6.5	67	15.9	102
(53-ft. depth)	0540	16.0	6.1	61	0615	6.0	60	15.8	99
(53-ft. depth)	1615	17.0	6.1	62	1710	6.1	63	15.5	101
Turbine boil									
(5 MW)	0755	16.0	8.1	82	0825	8.0	80	20.2	127
(10 MW)	1055	16.5	6.5	66	1115	6.3	64	16.9	107
(15 MW)	1345	17.5	6.1	63	1410	6.1	62	15.9	103
(35 MW)	1545	17.5	6.4	65	1750	6.3	65	15.6	101

1. Samples all processed on day collected - 24 Sep 72.

2. During the test period, additional generation data were recorded as follows:

Time (hr.)	MW	Discharge (cfs)	Tailwater level (ft.)
0500	5	2,125	11.20
0600	5	2,125	10.40
0700	5	2,125	10.15
0800	10	2,350	10.10
0900	10	2,350	10.10
1000	10	2,350	10.10
1100	15	2,660	10.10
1200	15	2,660	10.15
1300	15	2,660	10.15
1400	35	4,350	10.20
1500	35	4,350	10.70
1600	35	4,350	10.75

TABLE 13. Dissolved oxygen and nitrogen values for Mactaquac area water samples, 17 Sep 69.[1,2]

Sample location	Sample time (hr.)	Water temp. (°C)	O_2(Winkler) ppm	O_2(Winkler) % sat.	O_2(Scholander) ppm	O_2(Scholander) % sat.	N_2(Scholander) ppm	N_2(Scholander) % sat.
Reservoir, near hatchery intake pipe								
(1-ft. depth)	1025	17.2	6.4	65	5.7	58(44)	14.6	92(72)
(20-ft. depth)	1030	16.8	6.1	62	5.7	58(44)	14.7	92(72)
(40-ft. depth)	1030	14.5	6.2	60	5.4	53(42)	17.3	105(85)
(60-ft. depth)	1035	14.0	6.2	59	5.8	55(45)	17.7	107(87)
(90-ft. depth)	1045	13.5	4.9	47	4.5	43(35)	18.4	110(91)

1. All samples analysed by the Scholander method were processed on 18 Sep 69, beginning at 0900 hr., the day following their collection.

2. Figures in parentheses represent % saturation at 5°C.

TABLE 14. Dissolved nitrogen values for samples of aerated distilled water, 02 Nov 68.[1]

Samples	Water temperature (°C)	N_2 (Gas partitioner) ppm	% sat.
A	10	18.3	100
B	22	15.1	101
C	34	12.7	101

1. These tests were conducted by consultant chemists, Sproul and Woodard, University of Maine. Three samples of distilled water were saturated by bubbling air through them for 24 hours, at three different temperatures, to determine the accuracy of the method (gas partitioner) used.

TABLE 15. Dissolved nitrogen values for samples of aerated distilled water and aerated Saint John River water, 25-27 Sep 69.

Samples	Date	Water temperature (°C)	Hours of operation	N_2 (Scholander) ppm	% sat.
Aerated distilled water	25 Sep 69	20.6	0	14.6	101
	25 Sep 69	21.2	5	14.7	101
	25 Sep 69	20.3	11	15.1	102
	26 Sep 69	18.7	22	15.5	101
	26 Sep 69	19.2	24	15.5	103
	26 Sep 69	19.3	29.5	14.99	100
	27 Sep 69	18.9	48	15.0	101
Aerated Saint John River water[1]	25 Sep 69	17.7	0	16.4	106
	25 Sep 69	19.9	5	15.3	103
	25 Sep 69	20.0	11	14.9	100
	26 Sep 69	18.4	22	15.7	103
	26 Sep 69	18.9	24	16.1	107
	26 Sep 69	20.2	29.5	15.3	103
	27 Sep 69	21.5	48	15.2	105

1. The Saint John River water sample was collected from the Mactaquac reservoir, at the hatchery intake pipe three feet below the surface. The 6-L sample was placed in an open bucket at the hatchery, where a pump and stone were used to aerate it for 48 hours at room temperature.

TABLE 16. Dissolved nitrogen values for samples of aerated distilled water, 23-25 Sep 72.[1]

Sample	Water temperature (°C)	N_2 (Scholander) ppm	% sat.	N_2 (Van Slyke) % sat.
1	17.0	16.0	102	105
2	17.0	16.4	105	105
3	17.0	16.3	104	105

1. Samples were aerated for 24 hours.